

Application Note

Understanding Harmonics in Power Distribution Systems

Introduction

Certain types of non-linear loads can generate harmonics within a power distribution system. The harmonics can cause abnormal heating within transformers, neutral conductors, induction motors, etc. This application note provides some background on the harmonic problem and suggests some methods for measuring harmonics and minimizing their effects.

1. What are harmonics?

Harmonics are currents or voltages which have frequencies that are integer multiples of the fundamental power frequency. Each has a name associated with the multiplying number, i.e., if the fundamental frequency is 60 Hz, then the second harmonic is 120 Hz, the third is 180 Hz, etc.

2. When do harmonics occur?

Harmonics can be present in either voltage, current or both. They occur whenever the wave shape is distorted, i.e., when the wave shape varies from a pure sine wave.

Electric Utilities typically generate a voltage which is very nearly a sine wave. If an end user connects a linear load such as a resistive heater, the resulting current will be a sine wave and no harmonics will be present. If, however, the load is non-linear, drawing short pulses of current within each cycle, the current wave shape will be distorted (non-sinusoidal) and harmonic currents will flow. In a typical case, each harmonic will have a different amplitude depending on the type of distortion but, in general, the greater the distortion, the larger the

harmonic currents. The total current will be a combination of the fundamental plus each of the harmonics.

3. What types of loads generate harmonic currents?

In addition to arc furnaces, the commonly found loads which produce harmonic currents include the equipment containing semiconductors that switch the current on and off abruptly during each line cycle. Examples include variable speed motors, solid state heating controls, certain types of fluorescent lighting, electronic and medical test equipment, electronic office machines such as personal computers, printers, etc.

The particularly worrisome loads are personal computers (due to their large number) and the variable speed motors due to their occasional large size.

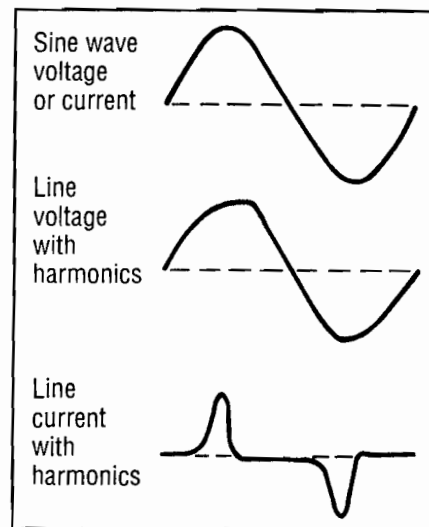
Voltage Harmonics

4. How are line voltage harmonics generated?

Distortion and harmonics on the line voltage are caused by harmonic currents acting in an Ohm's law relationship with the power source impedance, i.e., $E = I \times Z$. For example, a 10A harmonic current being drawn from a source impedance of 0.1 ohm will generate a harmonic voltage of 1.0 volt.

5. What problems are associated with harmonics on the line voltage?

Line voltage harmonics can radiate interference into telephone and communication systems. In addition, harmonics on the line voltage will



generate harmonic currents in linear loads such as induction motors and power factor correction capacitors. Induction motors are particularly vulnerable to higher frequency voltage harmonics for two reasons: 1. The eddy current losses within the motor are proportional to the frequency squared and 2. Certain harmonics, notably the 5th, are "negative sequence" which means they are backwards rotating. Good practice rules for motors dictate that the total harmonic distortion on the line voltage should be less than 5%.

6. How can line voltage harmonics be reduced?

Looking at Ohm's law in answer #4, it is clear that line voltage harmonics can be reduced by: 1. Using filters, etc. to reduce the harmonic currents or, 2. Making the power source impedance lower by installing a larger transformer,

larger and shorter conductors, better connectors, etc. Induction motor installations should be planned so that motor branch circuits are not shared by loads generating harmonic current.

Current Harmonics

7. What electrical problems are associated with harmonic currents?

Harmonic currents generated by non-linear loads will flow through components of the electrical distribution system including circuit breakers, conductors, busbars, panels, transformers, generators, etc. In most cases, these components were sized and/or designed to handle 60 Hz loads. When sizeable harmonic currents are present, problems are likely. The following discussion describes some of the potential problems associated with the parts of the distribution system:

Circuit Breakers-If the trip mechanism is not designed to respond properly to the higher frequency elements of the harmonic currents, the breaker may trip prematurely at a low current or fail to trip at the rated trip current. A breaker rated to respond to the true rms or heating value of the current will have a better chance of protecting against harmonic current overloads.

Conductors-In three phase systems, certain harmonic currents can overload neutral conductors. The troublesome harmonics, called "triplens", consist of the 3rd and odd multiples of the 3rd (i.e., 3rd, 9th, 15th, etc.). These harmonics will add rather than cancel in the neutral of a three-phase 4-wire system. Normally, the neutral carries only the unbalanced part of the phase currents but when triplens are present, it is theoretically possible to have neutral current at the triplen frequency that is 1.73 times greater than the phase current even if the phase currents are perfectly balanced.

Bus Bars and Connecting Lugs-Neutral bus bars that are sized to carry the full value of the rated phase current can become overloaded when the neutral conductors are carrying the additional sum of the triplen harmonics. Connecting lugs are vulnerable to the same problem.

Electrical Panels-Electrical panels that are designed to carry 60 Hz currents can become mechanically resonant to the magnetic fields generated by higher frequency harmonic

currents. Under these conditions, the panel can vibrate and emit an audible buzzing sound at the harmonic frequency.

Transformers-Transformers don't like harmonics for two reasons. First, the core losses caused by eddy currents and hysteresis tend to increase as the frequency goes up. Copper losses due to "skin effect" also increase with frequency. Second, harmonics can cause certain delta-wye transformer configurations to experience a circulating current in the delta winding. A common example would be the 208/120 volt transformers that commonly feed receptacles in a commercial building. In this case, single phase non-linear loads connect to the receptacles that can produce "triplen" harmonics which algebraically add in the neutral. When this neutral current reaches the transformer it is reflected into the delta primary where it circulates. The end result is transformer heating sometimes causing failures.

Generators-Standby generators can experience the same kind of overheating problems that affect transformers. In some cases, they are more vulnerable than transformers because they are used to provide emergency power for harmonic producing loads such as data processing equipment. In addition to overheating, certain types of harmonics produce distortion at the zero crossing of the current waveform, thereby causing interference and stability problems for the generator's control circuits.

8. What type of harmonic currents can be expected from single phase loads such as personal computers?

Personal computers are part of a large class of electronic equipment that employs diode-capacitor power supplies. These power supplies convert the ac line voltage to low voltage dc. The conversion process involves charging large capacitors each line cycle with narrow pulses of current that are time-coincident with the peaks of the line voltage. This process generates odd harmonics which are mostly 3rd and 5th with lesser amounts of 7th, 9th, etc.

Note carefully that the 3rd and the 9th are "triplens" which will algebraically add in the 3-phase neutral causing conductor overloading and transformer heating.

9. What harmonics can be expected from variable speed motor drives?

The frequency converters commonly used to drive variable speed motors are built in two types - 6 pulse or 12 pulse units. They are named according to the number of pulses produced for each cycle of the output variable frequency. The primary harmonics produced are equivalent to the pulse number plus or minus one, i.e., a 6 pulse convertor will generate 5th and 7th harmonics and a 12 pulse unit will generate 11th and 13th.

Test Instruments

10. What equipment is used for measuring harmonics?

The type of equipment used depends on the extent of the measurements required. If we want a real time picture of the wave shape, we would use an oscilloscope or digital recording instrument. If we want to determine the amplitude of each individual harmonic, we would use a spectrum analyzer. However, if we simply want to measure the true rms value or the instantaneous peak value of the wave shape, we can use a hand held digital multimeter. In power distribution systems we are usually more interested in the current than the voltage so in each case above the measuring instrument would be equipped with a current clamp so that the current could be observed without breaking conductors.

11. What is meant by the term "TRUE RMS"?

The term "TRUE-RMS" relates to the root-mean-square or equivalent heating value of a current or voltage wave shape. The root-mean-square terminology comes from the mathematical formula that says if a distorted waveshape and a pure sine waveshape produce the same amount of heat in a resistive load then the two waveshapes have the same rms value.

The word "TRUE" comes from the fact that not all instruments give correct readings for distorted wave forms. The vast majority of low cost portable instruments are "average responding - rms calibrated". These instruments give correct readings for sine waves only and will typically read low when the waveform is distorted. The more expensive instruments equipped with true-rms convertors will

give correct readings for any wave-shape within the crest factor and bandwidth limitations.

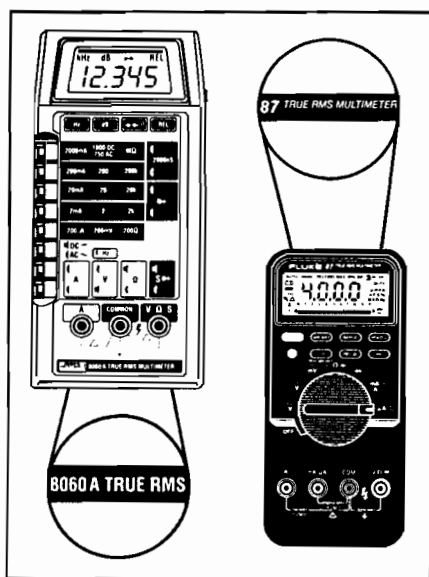
When harmonics are present, a true-rms responding instrument is required for correct readings because the true-rms value relates directly to the heat produced in conductors, transformers and other components of a power distribution system.

12. What is a "crest factor"?

The crest factor of a waveform is the ratio of the peak value to the rms value. For a sine wave, the crest factor is 1.414. A true-rms measuring instrument will have a crest factor specification which relates to the amount of peaking that can be measured without errors. Typical specification numbers would range from 2.0 to 7.0. The higher the number the better the performance. A typical handheld digital multimeter would have a crest factor specification of 3.0 which would be adequate for most power distribution measurements.

13. Is there an easy way to identify a true-rms measuring instrument?

Most handheld and portable test instruments are labeled on the front panel if they have true-rms capability. Look near the model number or near the AC function control. The label should read "TRUE-RMS" or "T-RMS". Two examples are shown.



If the label is missing, chances are that the instrument is average responding. A second place to look would be the instrument's performance specifications. Look under the AC volts sec-

tion for a statement about the converter type or calibration scaling. A properly specified true-rms instrument will always have a crest factor specification.

14. What Fluke Models are recommended for true-rms measurements in power distribution systems?

Fluke currently makes four models of true-rms handheld digital multimeters: Models 8026A, 8060A, 8062A and 87. The Model 8060A is the most accurate but Model 87 is recommended for most applications because it has the additional features of peak hold, min/max and average recording. Recommended accessories for the above models include 80i-600 and 80i-400 AC current probes and 80i-kW current/power probe.

Survey Methods

15. What steps should be taken to make a facility survey for harmonic currents?

The following list suggests a sequence of steps for a harmonic current survey:

- a. Load Inventory-** Make a walking tour of the facility and note which loads are likely to generate harmonic currents (see question 3).
- b. Transformer Heat Check-** Locate the transformers feeding the potential problem loads and look for excessive heating. Check for blocked cooling vents, etc.
- c. Transformer Secondary Current-** Use true-rms measuring equipment for checking transformer currents. First, verify that the voltage ratings for the test equipment are adequate for the transformer being tested. Then, measure and record the transformer secondary currents in each phase and the neutral (if used). Next calculate the kVA being delivered to the load and compare it to the nameplate rating (see examples in question 17). Note that if harmonic currents are present, the transformer can overheat even if the kVA being delivered is less than the nameplate rating.

If the transformer secondary is a 4-wire system, compare the measured neutral current to the value predicted from the imbalance in the phase currents. (The neutral current is the vector sum of the phase currents and would normally be zero if the phase

currents are balanced in both amplitude and phase.) If the neutral current is unexpectedly high, triplen harmonics (question 7) are likely and the transformer may need to be derated as described in question 17.

Next, measure the frequency of the neutral current. 180 Hz would be a typical reading for a neutral current consisting of mostly 3rd harmonic.

d. Sub-Panel Neutral Current Check- Survey the sub-panels that feed harmonic loads. Measure the current in each branch neutral and compare the measured value to the rated capacity for the wire size used. Check the neutral busbar and feeder connections for heating or discoloration.

e. Receptacle Neutral-to-Ground Voltage Check- Neutral overloading in receptacle branch circuits can sometimes be detected by measuring the neutral-to-ground voltage at the receptacle. Make the test when the loads are on. 2V or less is probably normal. Higher voltages can indicate trouble depending on the length of run, quality of connections, etc. Be particularly cautious about under carpet wiring and modular office panels with integrated wiring that use a neutral shared by three phase conductors. These have been troublesome in the past due partially to the fact that typical loads are computer and office machines that generate triplen harmonics which overload neutrals.

16. Is there an easy way to detect harmonic currents without using an oscilloscope or harmonic analyzer?

Yes, in some cases. If the harmonics in question are the lower frequency variety such as those produced by personal computers and business machines, the current wave-form will contain narrow pulses consisting mostly of 3rd, 5th, and 7th harmonics. Waveforms of this type have a true-rms value that is substantially higher than the average value. The presence of harmonics can be established by measuring the difference between the true-rms value and the average value.

First, measure and record the phase current using a meter that responds to the average value. Next, measure the phase current with a true-rms meter and compare the readings. If harmonics are present, the true-rms meter will have a higher reading. The greater the

difference, the more harmonics are present. **Caution Note:** the comparative readings should be made on the phase conductors, not the neutral. In cases where the harmonics are mostly 3rd, the neutral current can be a nearly pure sine wave at the harmonic frequency of 180 Hz. Triplen harmonics, such as the 3rd which add in the neutral can often be detected by measuring the frequency of the neutral current.

SOLUTIONS

17. What can be done about overloaded neutrals?

In a 3 phase 4-wire system, the 60 Hz portion of the neutral current can be minimized by balancing the loads on each phase. The triplen harmonic neutral current can be reduced by adding harmonic filters at the load. If these solutions are not practical, extra neutrals may have to be pulled in. One neutral for each phase is ideal. An alternative would be an oversized neutral shared by 3 phase conductors.

In new construction, under carpet wiring and modular office partitions with wiring should be specified to have individual neutrals and possibly an isolated ground separate from the safety ground.

18. What procedures are available for calculating a derating factor for receptacle transformers?

The most rigorous method for derating transformer capability is given in ANSI/IEEE standard C57.110-1986. This method is somewhat impractical, however, because it requires extensive loss data from the transformer manufacturer plus a complete harmonic spectrum of the load current. A second method has recently been recommended by the CEBMA Association (Ref. 1). This method involves several straight forward measurements that can be made with commonly available test equipment. It appears to give reasonable results for 208/120 Y receptacle transformers that supply low frequency odd harmonics (3rd, 5th, 7th) that are commonly generated by computers and office machines.

Using this derating method, it is necessary to measure both the true rms phase current and the instantaneous peak phase current for each phase of the secondary. While the measurements are simple enough to

make, the test equipment must be capable of taking true rms and instantaneous peak current measurements.

To determine the derating factor for the transformer, the peak and true rms current measurements are taken for the three phase conductors. If the phases are not balanced, the numbers used in the formula should be an average of the three phases.

THDF = Transformer Harmonic Derating Factor

$$= \frac{(1.414)(\text{True RMS Phase Current})}{(\text{Instantaneous Peak Phase Current})}$$

This formula generates a value between 0 and 1.0, although typically between 0.5 and 0.9. (Note that if the phase currents were purely sinusoidal, the instantaneous peaks would be 1.414 times the true rms value, and the derating factor would be 1.0; i.e., no derating.) The transformer rating with harmonics present would be the product of the nameplate KVA rating times the THDF.

KVA derated = (THDF)(KVA nameplate)

Example for 208/120 Y transformer rated at 125 KVA:

Measured values for the load currents were recorded as follows using a Fluke Model 87 and an 80i-600 ac current probe accessory.

Conductor Name	True rms Current Amps	Instantaneous Peak Current
φ1	205A	402A
φ2	221	446
φ3	218	414
I phase avg. = $\frac{205 + 221 + 218}{3} = 214A$		
I pk avg. = $\frac{402 + 446 + 414}{3} = 420A$		
THDF = $\frac{(1.414)(214)}{420} = 72\%$		

This calculation indicates that with the level of harmonics present, the transformer should be derated to 72% of its rating to prevent overheating.

19. Can harmonics cause problems for power factor correction capacitors?

Yes, power factor correction capacitors can form a resonant circuit with the inductive parts of a power distri-

bution system. If the resonant frequency is at or near one of the harmonics, the harmonic current can increase substantially overloading the capacitors and blowing the capacitor fuses.

Common practice for linear loads dictates that the capacitors should be placed as close to the load as possible. This practice is not recommended when harmonics are present because the likelihood of a resonance condition is typically increased as the capacitors are moved electrically closer to the load. Recent articles on the subject recommend using inductive reactors in series with capacitors so that the series combination looks inductive to the lowest harmonic of interest, (Ref. 2).

References

1. Freund, A. : "Double the Neutral and Derate the Transformer - Or Else", EC & M, Dec. 1988, Pg. 81.
2. Barnes, R. : "Harmonics in Power Systems", Power Engineering Journal, Jan. 1989, Pg. 11.

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